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Technical note

Design, optimisation and testing of a compact, inexpensive elastic element for series elastic actuators

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ABSTRACT

This paper presents the development of a compact torsion spring for use as an elastic element in a lightweight series elastic actuator for an active orthosis. This orthosis is going to be utilised as an assistive device for motorically impaired stroke-patients. In the design a two-step optimisation strategy was implemented to meet all requirements for the torsion spring. The first step was to identify a promising topology for the element. In the second step, the shape was optimised based on a finite element model using two different optimisation methods in order to minimise the von Mises equivalent stresses. Four promising variants of the identified topology were extracted from these calculations, one of which was then chosen as the final design. A prototype was manufactured by a laser cutting process, which is a new procedure in the context of elastic elements for series elastic actuators. The calculation results were validated successfully by measurement of the spring properties of this prototype.

1. Introduction

Stroke is a common disease in modern society and considering the ageing of society a rise of cases is to be expected over the next years [1,2]. Stroke leads to temporary or permanent damage of parts of the patient's brain, often resulting in motor or cognitive deficits, depressions or hemiparesis [3]. It is possible to regain lost abilities with the help of intensive training with equally intensive therapeutic support.

The use of actuated orthoses is an approach for enhanced physiological therapy of motorically impaired patients. They allow for intensified rehabilitation-training without imposing further workload on therapists [4]. However, strict safety requirements have to be fulfilled because of the close physical interaction between patient and device. Main demands regarding the actuation are that the patient must have the choice to override the force exerted by the orthosis e.g. in case of an unexpected event during a training session for gait rehabilitation. Therefore, rigid movements along prescribed patterns are not acceptable which implies the need for controlling interaction forces rather than positions [5]. Also the device should be able to be fully transparent, in other words it should not exert any force on the wearer when no support is needed, which is another reason for the need of interaction force control [6,7]. Because wearable devices are more efficient and easier to handle if they are compact and light, the device should be as small and lightweight as possible. The following section shows that series elastic actuators (SEA) are a promising concept to fulfil all the above requirements (possibility to override device motions, interaction force control, compact design, lightweight). Consequently, the active orthosis which is currently under development at the University of Magdeburg is intended to support basic leg movements of stroke patients by an SEA.

A number of literature reviews on the subject of lower-limb robotic rehabilitation have appeared in recent years (e.g., [8], [9]). Several stationary walking robots are commercially available for gait rehabilitation [10–14] as well as several wearable robots for gait assistance and gait rehabilitation [15–20]. None of these commercially available wearable devices utilise SEA.

Other applications for SEA besides the wearable robots include legged robots [21–23] and robotic arms for interaction with humans, e.g. teach-repeat-programmable arms [24] or an autonomous feeding robot [25]; in general fields where robots have to deal with impacts and/or unknown environments.

Series elastic actuators Principally, an SEA consists of an electric gear motor[2] and the torsion spring connected in series with motor and load [26]. The arrangement has numerous advantages.

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[2] fluidic SEA are not considered because of their high mass.

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Table 1
Main properties of elastic elements shown in Fig. 1 in comparison to the requirements for new torsion spring.

	Diameter	Thickness	Max. Torque	Torsional stiffness	
Spring a – [27]	75 mm	15 mm	100 Nm	219 $\frac{\text{Nm}}{\text{rad}}$	3.82 $\frac{\text{Nm}}{\text{deg}}$
Spring b – [7]	85 mm	3 mm	7.7 Nm	98 $\frac{\text{Nm}}{\text{rad}}$	1.71 $\frac{\text{Nm}}{\text{deg}}$
Spring c – [30]	90 mm	11 mm	60 Nm	250 $\frac{\text{Nm}}{\text{rad}}$	4.36 $\frac{\text{Nm}}{\text{deg}}$
Spring d – [31]	125 mm	6 mm	15 Nm	84 $\frac{\text{Nm}}{\text{rad}}$	1.47 $\frac{\text{Nm}}{\text{deg}}$
Design objective	max.60 mm	max.10 mm	15 Nm	172 $\frac{\text{Nm}}{\text{rad}}$	3 $\frac{\text{Nm}}{\text{deg}}$

1. Measuring the deformation of the elastic element enables calculation of the torque exerted on the load through application of Hooke's Law [26]. Using an elastic (in other words: compliant) element makes it very simple to quantify the action of the patient. Therefore the device does not need additional force sensors measuring the contact force between the patient's leg and the orthosis to determine the controller-input.
2. The spring deflection can be measured by quantifying the difference between rotation angle before (φ_1) and after (φ_2) the elastic element. Therefore the position φ_1 needs to be adjusted by the controller, which is more accurate than force transmission. This in turn means that an SEA allows for utilising inexpensive, lightweight motor and gear with lower force fidelity [26]. Moreover, a spring reduces the effects of stiction and backlash in the motor and gearbox, which reduces the requirements for the latter parts even further [27].
3. Compliant elements connected to a mass are characterised by a low-pass filter behaviour and can therefore keep away high frequency disturbances from the gear motor.
4. The demand for transparency requires zero-force-control, which cannot be achieved by an actuator with stiff connection between load and motor [28]. Hence, the application of a compliant element means a considerable improvement in comfort for the wearer of the orthosis.

The spring characteristics play a decisive role for the properties of the SEA and have to be chosen carefully. A lower stiffness results in a higher torque resolution, yet, also a lower controller bandwidth because a softer torsion spring shows a bigger deflection at a given torque. Consequently, an increased angle of rotation has to be provided within a given time interval, which requires faster acceleration of the motor. Since motor torque limits the acceleration, the controller bandwidth is reduced when spring stiffness is reduced [29]. Therefore, a compromise has to be found between high torque resolution and controller bandwidth.

1.1. Elastic elements for series elastic actuators

Currently, no standard solutions for elastic elements exist because the purposes of SEA are very individual. Numerous designs of elasticities with different specifications have been proposed. These can be separated into two types: Multi-part and single-part elasticities. Single-part elasticities are more suitable to achieve a lightweight and compact solution which meets the required spring characteristics of one particular application; Fig. 1 shows seven possible realisations of this type. Main properties of the elements a–d are summarised in Table 1, whereas no data was available for elements e–g.

1.2. Design objectives for the new torsion spring

The main design objectives of the elastic element being developed are shown in the last row of Table 1. The very compact installation space prescribed is one major difference between former realisations and the new elastic element. Hence, a new design is proposed in this paper. Besides satisfying the geometric requirements, the elastic element needs to be as lightweight as possible and the solution is wished to be as cost effective as possible. That is why maraging-steels as used for springs a–c in Fig. 1 (no information available about springs e and f) and titanium alloys were not considered. As shown in Section 2.1, realisations with equivalent stresses (von Mises) below 600 MPA are attainable. Considering the required safety factor amounting to 2, the material needs to have a yield strength of at least 1200 MPA. In a material study the group of spring steels was found to contain sufficient materials satisfying this requirement, for example 56Si7 and 55Cr3.[3]

2. Design of the elastic element

The design process had two main steps. Firstly, identifying a topology able to fulfil all requirements mentioned above and secondly, deriving a detailed design from that topology as starting point for an FEM-based geometry optimisation with the objective to minimise the maximal equivalent stress. The dimensions of neighbouring actuator-parts were considered during the creation of the detailed design.

2.1. Determination of a suitable topology

The basic model used to determine the geometry consisted of two rings (width: 4 mm) connected by flexible elements to achieve spring characteristics. The outer ring was defined to have the biggest allowable diameter of 60 mm in order to use as much space as possible for the compliant structures. Also, the component thickness was set to the maximal allowable value of 10 mm to use as much material as possible, leading to lower maximal stresses. The outer diameter of the inner ring was set to 18 mm.

A topology optimisation carried out to calculate a compliant structure of the elastic parts connecting the two rings did not lead to sufficient results. Therefore a suitable topology was identified by variation of literature examples. An analysis of the elastic elements shown in Fig. 1 led to the conclusion that a long force transmission path is desirable for the elastic element. With long force transmission paths, the required stiffness can be achieved with wider cross-sections, which in turn leads to lower equivalent stresses. The elements a, b and d shown in Fig. 1 were tested during the process of geometry-identification. They were modelled as parametric CAD parts and were made comparable by carrying out a quick FEM-based geometry optimisation within the CAD software in order to achieve the required spring characteristics. Considering the length of the force transmission path, element a could be expected to show the lowest equivalent stress, followed by element d and b. These expectations were confirmed by the pre-calculations. Fitting the geometry of element b to the desired spring characteristics resulted in very small wall thicknesses, giving two disadvantages: Firstly, the calculated equivalent stresses were very high and secondly, a very accurate and therefore slow and expensive production process would be needed to achieve the demanded spring

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[3] Material numbers according to EN 10027: 1.5026 and 1.7176, respectively.

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